RECENT PROGRESS IN DoD's PROGRAM TO DEVELOP Ar K-Shell X-RAY RADIATION SOURCES

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Abstract

The Decade Half x-ray radiation simulator will combine the outputs of eight synchronized modules to produce a current of up to 13 MA delivered to a short circuit load in ~300 ns. Decade is located within the Decade Radiation Test Facility (DRTF) at the Arnold Engineering Development Center, Tullahoma, TN. Decade's output will be used for nuclear weapons effects testing; the DRTF will reach initial operational capability (IOC) in 2007.

DoD's X-ray Radiation Simulator R&D Program is focused on maximizing 3.1 keV x-ray fluence from Decade's argon z-pinch. Electric current risetime will be approximately a factor of 3 longer than typically used to drive plasma radiation source (PRS) loads. Scaling to longer current risetime is advantageous in terms of reduced driver cost and complexity. The use of longer pulse drivers, however, requires an increase in the initial diameter of the z-pinch gas puff. The unique challenge is to extend the success with 100 ns current risetime simulators into the realm of the 300 ns current risetime of Decade. As the diameter is increased, increased asymmetry and instability can limit the ability of the load to produce K-shell radiation efficiently. These effects were largely un-quantified until technical investigations were conducted under the auspices of the Simulator R&D Program. This paper discusses progress, activities and issues in developing the large diameter z-pinch for Decade.

Figure 1. Decade Quad machine presently on the floor at the DRTF. A second "quad" will be added before 2007.

I. PROGRAMMATICS

Specific R&D objectives are to demonstrate 1) that over 120 kJ of argon K-shell radiation will be produced by Decade's 13 MA, 300 ns current with a large diameter (>10 cm) PRS nozzle, and 2) that unwanted debris and ultraviolet radiation from this source can be stopped by a debris mitigation system. Figure 2 lists program areas, across the top, program objectives, and capabilities being supported. "CTEIP" is the abbreviation for DoD's Central Test and Evaluation Investment Program that ensures operability of DoD test facilities. The Simulator R&D Program is attempting to ensure that diagnostics systems developed earlier (e.g., see [1]) are implemented on demonstration experiments, and that results are integrated into analytic tools and computer models.

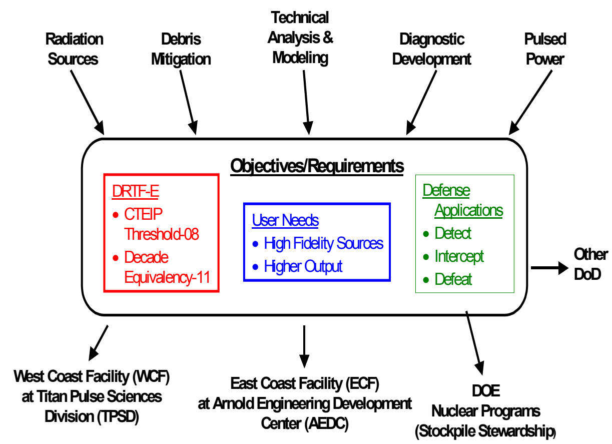

Figure 2. DoD Simulator R&D program areas, objectives and capabilities supported

The program's recent pulsed power efforts have supported development of new, advanced capacitors – presentations later in PPC 2003 will discuss achievements and plans to use the new capacitors in several applications, to include future Decade upgrades.[2,3] DoD's Simulator R&D Program also is supporting efforts to ensure that a gamma radiation (> 3 MeV) simulator and a debris electron simulator to be installed in the DRTF will operate properly. The technical analysis and modeling area supports rigorous simulator team efforts to apply previously developed skills, analytical tools and computer models to these objectives.

0-7803-7915-2/03/$17.00 ©2003IEEE.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Recent Progress In Dods Program To Develop Ar K-Shell X-Ray Radiation Sources**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **aDefense Threat Reduction Agency; bNaval Research Laboratory; cAlameda Applied Sciences Corporation,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License, The original document contains color images.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

II. RECENT PROGRESS

Significant progress has recently been made in high current, long implosion time z-pinches in efforts to scale up to a large diameter nozzle for Decade.[4] In November 2001, 28 kJ of argon K-shell radiation was produced by a 214 ns, 4.7 MA peak current through an 8-cm diameter nozzle (300 μg/cm line-mass) on Decade Quad (see Fig. 3). In July 2002, over 300 kJ was produced by a 117 ns, 14.3 MA current through the same 8-cm nozzle (800 μg/cm) on the Z-machine at Sandia National Laboratories, Albuquerque (SNLA). In the last year, 7-9 kJ was demonstrated with 230-240 ns, 3.5 MA currents through 12-cm nozzles (185 μg/cm) on Double-EAGLE at DTRA's West Coast Facility.[5] In addition, success in the long implosion time regime has been demonstrated on Decade with a high quality pinch producing >40 kJ K-shell output from a large diameter, aluminum wire array load imploding in >250 ns.

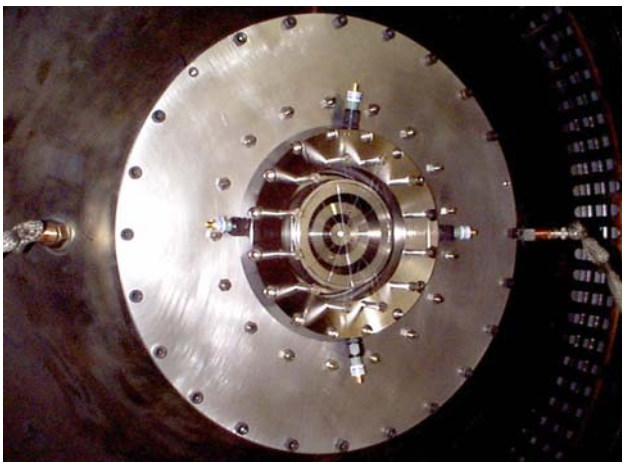

Figure 3. PRS Nozzle (8-cm) installed on Decade produced 28 kJ (3.1 keV) with 214 ns, 4.7 MA peak current

These tests confirm for the first time that, with an appropriate radial mass distribution, larger PRS loads can be sufficiently stable for significant x-ray production.

With regard to energy coupling, scaling of K-shell radiation yield with load current has been well established for up to 15 MA.[4] As indicated in Fig. 4, yield changes as I^4 at lower currents and as I^2 above 4MA. For high currents, the K-shell yield appears to be as efficient a radiator for large diameter, long implosion time loads as small diameter, shorter implosion time loads.[6]

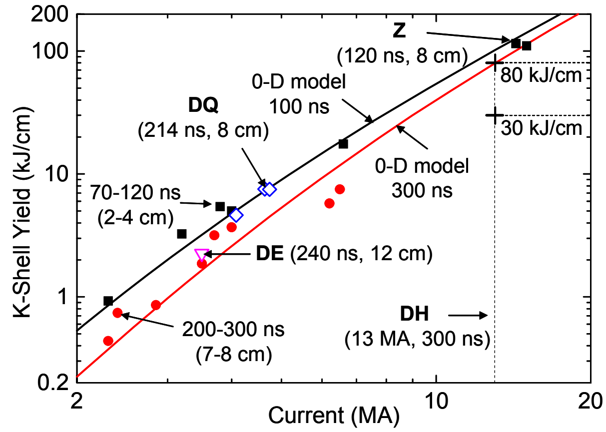

Figure 4. Zero-D scaling predictions for ~100 (upper curve) and 300 ns (lower curve) implosion loads, compared with data from past experiments (squares, circles) and more recent results from Decade Quad (DQ) and large diameter nozzles on Double Eagle (DE). Decade Half (DH) will operate at 13 MA (or less) with the goal of producing at least 120 kJ (30 kJ/cm × 4 cm).

The most important issues affecting load design on a long pulse machine are directly related to the need to deliver as much of the machine energy as possible to a load, so that it has enough specific energy to be able to radiate efficiently, i.e., in the I^2 regime. The specific energy is often expressed in terms of η*, which is a measure of the $J \times B$ coupled energy per unit mass, relative to the energy required to ionize to the K-shell. The strong dependence of K-shell yield on η* has been demonstrated experimentally on Decade, Z, and on the Saturn machine at SNLA (see Fig. 5). Note that 0-D models do not capture the observed fall-off in K-shell radiation with increasing mass and decreasing η*. Evidently, with higher mass the final temperature is limited by losses (which scale as M^2) requiring greater η* values (increased diameter). The larger, 12-cm nozzle tested on Double-EAGLE was developed in order to provide favorable η* values for Decade loads.[7]

For Decade Half parameters and a 16-cm diameter nozzle, the goal yield of 120 kJ (30 kJ/cm × 4 cm) could be achieved at the 9-MA current level where η* ~ 4. Ideally, the yield could increase to 80 kJ/cm at 13 MA, but the specific energy would decrease to η*~1 and the 0-D prediction is probably optimistic for this high mass, based on empirical evidence like that in Fig. 5. The diameter would have to be increased to improve the prospects for efficient K-shell radiation at the full Decade Half current.

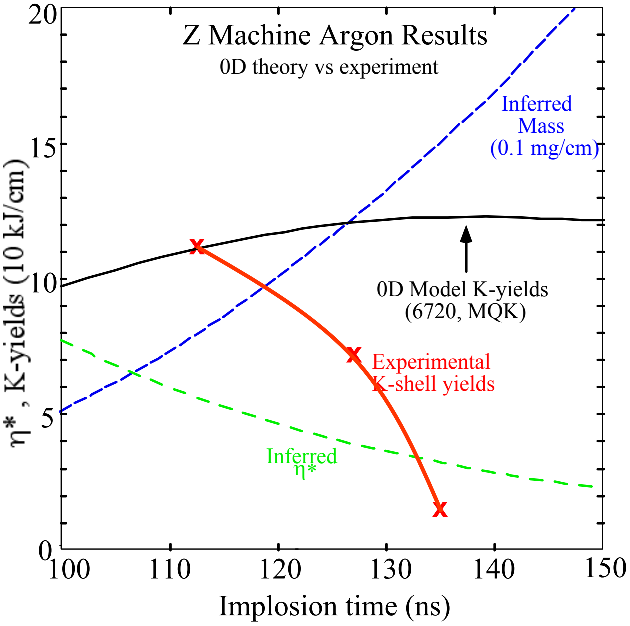

Figure 5. Experimental values for η* on Z and mass used to design larger PRS nozzles

Radiation output can be increased by increasing the efficiency of conversion of magnetic energy to radiation. The basic mechanism is magnetic-to-kinetic energy conversion, with kinetic energy thermalized at stagnation and subsequently converted into radiation. It has been known since the early 1980s that the plasma radiation source can radiate more energy than can be converted into kinetic energy through the work of the $J \times B$ force.[8] This excessive energy has been attributed to some kind of anomalous resistivity because classical (Spitzer) resistivity is too low to explain the discrepancy. In experiments with aluminum wire arrays on Saturn, the total radiated energy sometimes exceeded the magnetic energy by a factor of 3.5-4.[9]

It is not certain how much of this excess energy can be channeled into radiation in the K-shell or continuum in the 1-10 keV range. Theory yields an expression for enhanced plasma resistivity which is consistent with its first direct measurements made on a low current driver.[10] That is, some portion of the ½ LI^2 energy can contribute to further heating during the lifetime of the pinch. Applying scaling for Decade conditions, consider R(Ohms) = ½ I_{max}(MA) l(cm) $m^{-1/2}$(cm/μg) r_f^{-1}(mm^{-1}) = (½× 13 × 4)/(30 x 1) = ~ 1 Ohm, and, L (nH) = 2 × l(cm) ln (r_o/r_f) ~ 10 nH. Then, τ_{heat} ~ 10 ns, which is approximately the pinch duration, and indicates that energy may be increased beyond that available from kinetic energy of the implosion. The resistance could be sufficiently high to make L/R time associated with inductance-to-resistance energy transfer comparable with pinch lifetime.

III. PROGRAM PLAN

A number of additional factors need to be investigated before a successful full scale load can be delivered for use on Decade. Program participants are poised to begin the next campaign to demonstrate this nozzle. Efforts to scale-up to the larger nozzle are being conducted jointly by the Naval Research Laboratory (NRL), Alameda Applied Sciences Corporation and Titan Pulse Sciences Division. Other contractors and SNLA also support the effort, e.g., to supply various components, analysis, modeling and diagnostics. Several PRS working group meetings have been held over the last year; and, Dr. John Apruzese of the NRL is currently serving as the team chair/program area reviewer. Recently our Plasma Radiation Source (PRS) working group met and identified four key physics issues that need to be resolved before an optimum nozzle and load can be designed and implemented on Decade. These issues are:

(1) What are the optimum mass ratios for the shells (and a central gas jet) to optimize K-shell yield? What physics is involved in optimizing these ratios?

(2) How much yield comes from the various shells (and central jet) and what, if any, is the role of intershell mixing?

(3) What is the fate and the role of the "dark matter" in the implosion, that is, the mass which does not radiate K-shell photons?

(4) Can the use of a low-atomic-number gas in the outer shell, which would not lose much energy through soft x-ray cooling, improve K-shell yield from the inner shells (and a central jet)?

The approach used by the team is to attempt to improve all three phases of PRS operation – initial, magneto-hydrodynamic, and the final or x-ray production phase. Delivery of the prototype nozzle is planned in 2006.

Initial Phase - The initial phase includes the introduction of argon gas into the pinch region (over 100s of microseconds), introduction of very short wavelength vacuum spark ultraviolet light from flashboards (20-50 nm) to preionize the gas, introduction of the main current pulse into the gas and, the beginning of the pinch process. Neutral gas density in this phase is a few times $10^{16}/cm^3$ (varies with nozzle pressure). Preionization with UV light from a flashboard seems to improve shot consistency.[11] Symmetry with which UV light irradiates and ionizes the argon gas is an issue being investigated. Timing to initiate the main current pulse is typically adjusted to occur within a couple of microseconds after the flashboard is pulsed, so that pinch/x-ray production is completed before a significant amount of flashboard debris (velocity ~ 20 cm/μs) intercepts the pinch region. Flashboard UV intensity is able to ionize a few (1-10%) percent of the argon (current follows a damped, 5 microsecond period sinusoid). Uniformity appears to be important.[12] The degree of uniformity, however, is known to vary with time. Condensation of the gas into extremely small droplets due to its low temperature as it exits the nozzle may be a concern. More experiments will be needed to optimize mass distribution in scaling up to a larger nozzle.

Magneto-hydrodynamic Phase - During the magneto-hydrodynamic phase, the plasma moves toward the center of the pinch region in response to the main current, which at this time is increasing to its peak value. Symmetry and stability of the inward moving plasma are crucial and are influenced by tailoring of the argon mass distribution in the initial phase. Rayleigh-Taylor instability may be reduced when the current sheath accumulates mass ("snowplow" stabilization) as it moves inward.

X-ray Production Phase - Understanding of radiation transport during the final, x-ray production phase is of great importance in efforts to determine methods to increase yield of plasma radiation sources.[13] This phase lasts some tens of nanoseconds.

If argon K-shell yield from larger nozzles is not sufficient at 300-ns implosion times, alternatives will be investigated to shorten the current risetime. On Decade, this could be accomplished in a number of ways: modifying the pulsed power by additional capacitors (probably too expensive), using a plasma opening switch (POS), or using a different pulse compression technique (e.g., flux compression or current multiplier). A version of the POS technique is probably the best near-term choice because it has already been used to produce efficient coupling to PRS loads.[14]

IV. DIAGNOSTICS

Diagnostics for gas-puff PRS loads have recently improved considerably. Sets of x-ray detectors can be used to view different radial regions of the pinch to determine pinch diameter (time-dependent, axially-averaged). Two-dimensional shearing interferometry has enabled the shape of the advancing front during the implosion to be determined.

Spatially resolved electron densities, ion densities and ion temperatures can be determined in the pinched plasma with a space and time resolved Johann spectrometer. Holographic interferometry is also used to measure the 2-D electron density distribution. Magnetic field distribution during magneto-hydrodynamic and final phases of the pinch can be determined with Zeeman spectroscopy and bi-refringent interferometry.

The use of dopant ions in the argon has been very beneficial in studying plasma properties in a pinch near and at stagnation.[15] This will be discussed in another paper.[16] Gas doping provides reliable optically thin spectral lines. Ion velocities at the final phase of the implosion can be determined. Electron temperature, charge state distribution, ion velocities and magnetic field distribution can be investigated from the UV radiation.[17]

V. ACKNOWLEDGEMENTS

Information regarding programmatic status and plans may be obtained from R. Davis, Manager, DoD X-Ray Simulator R&D Program, Defense Threat Reduction Agency (DTRA), ATTN: TDNS, 8725 John J Kingman Rd Stop 6201, Ft Belvoir VA 22060-6201. The authors would like to thank B. Weber from the Naval Research Laboratory for presenting this material at 2003 PPC.

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